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EVALUATION OF PROCESSES PARAMETER AND MECHANICAL PROPERTIES IN FRICTION STIR WELDED STEELS

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ABSTRACT

The present study focuses on Friction Stir Welding of steel being very popular due to the vast application in the fields of automotive and ship building industries. The main constrained of welding steel has considered due to severe loads and temperatures at the interface of FSW tool and parent materials. Ti and pcBN based alloys are suitable for joining steel alloys up to 15 mm thick was found during study. Many researchers carried out study on FSW of steel and found on weld process parameters, mechanical properties, microstructure and the tool employed to produce the weld. It was found that carbon content, welding speed as well as the rotational speed affects between the mechanical properties and the microstructure of the weld.

Key words: Friction Stir Welding, Processes parameter, Tool geometry, mechanical properties, Microstructure.

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1. INTRODUCTION

In recent decade, the weight saving of automobile and ship building is one of the important parameter favoring the reduction in the energy consumption and hazardous emissions. As structural steel is strengthen by the addition of rare metals such as Ni and Mo. The tensile strength of structural steel can be increased by the addition of the amount of carbon content. So, it can be concluded that rare metals can be replaced by much cheaper carbon content [1, 2].

The Friction stir welding (FSW) is a novel solid state joining process developed in 1991 by The Welding Institute, Cambridge, UK. The FSW process is performed at much lower temperature than the conventional welding due to no melting behavior. It also allows to avoid environmental and safety issues [3, 4]. Therefore it has wide application potential in ship building, aerospace, automobiles and other manufacturing industries. With the development of FSW and highly durable rotating tools, this

technique has been applied to various high melting points metallic materials i.e., Cu, Ti, Fe and steels [5, 7]. Specially the high carbon steels can be welded using FSW technique, which was considered unweldable materials due to brittle martens tic plastic formation [8, 9]. To obtain optimal weld formation and mechanical properties, it is appropriate to design the tool shoulder diameter about three times the plate thickness. FSW provides wear resistance and high temperature stability. It is Tungsten, Polycrystalline cubic boron nitride (pcBN) and Si_3N_4 based which can join high strength materials such as titanium and steel alloys Si_3N_4 produced welds at much lower cost comparable at pcBN [10]. FSW was applied to Si_3N_4 based tool at different welding speed i.e., 50 to 300 mm/min and a constant rotation speed of 400 rpm to 2 mm thick high nitrogen containing stainless steel plates etc [11]. It has been successfully produced friction stir welds containing 0.7 wt% C and 1.02 wt% C steels at several welding parameters without any pre or post heat treatment and characterized stir zone microstructure with hardness profile. The result indicates marten site transformation is inevitable only in FSW process of high carbon steel [12]. To allow long tool life and reliable weld properties, polycrystalline cubic boron nitride (pcBN) tool are used in high melting materials [13].

Tool tilt angle is an added process parameter apart from rotating speed and traverse speed of the tool which provides better results in FSW of steel [12, 14]. Using different tool geometry, truncated pin has better joint strength because of easy penetration of the work piece materials which reduces tool pin failure [15].Several study has been completed on AISI 1018 steel, with 6.35mm materials thickness. Molybdenum and tungsten based alloy were utilized in FSW of steel whose travels speeds and rotational speed varies from 25.4 to 100 mm/min and 450 to 600 rpm respectively [16].

2. FRICTION STIR WELDING PROCESS

The joining process of work piece in the solid phase by FSW, which uses an intermediate non consumable tool made of a material that is harder than the work piece material being welded and then translated along the joining line as shown in fig.1. Together with suitable cyclic movement and the marked difference between the elevated temperature properties of the tool and the work piece, generates sufficient frictional heat to cause plasticized conditions in the work piece material. Thus, FSW is a condition of hot shear process which involves slowly plunging a portion of a specially rotating tool along the abutting faces of the joint. The probe length below the shoulder and the abutting faces of the tool's shoulder should allow the probe to maintain the penetration of required depth. To achieve the range of hardness and elevated temperatures of work piece materials there has to maintain the difference of these two properties of the tool and work piece materials.

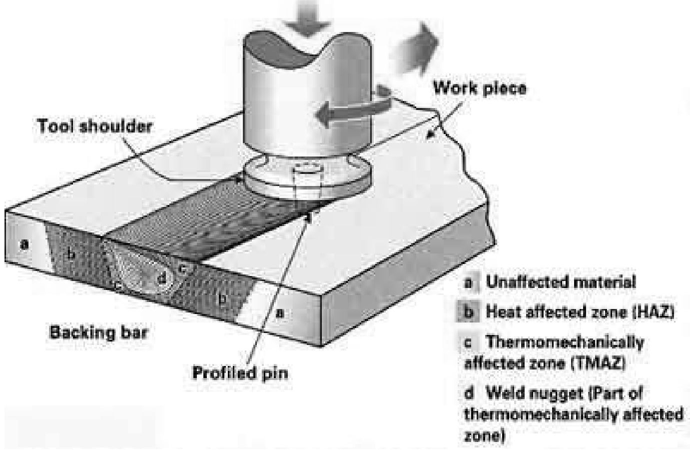


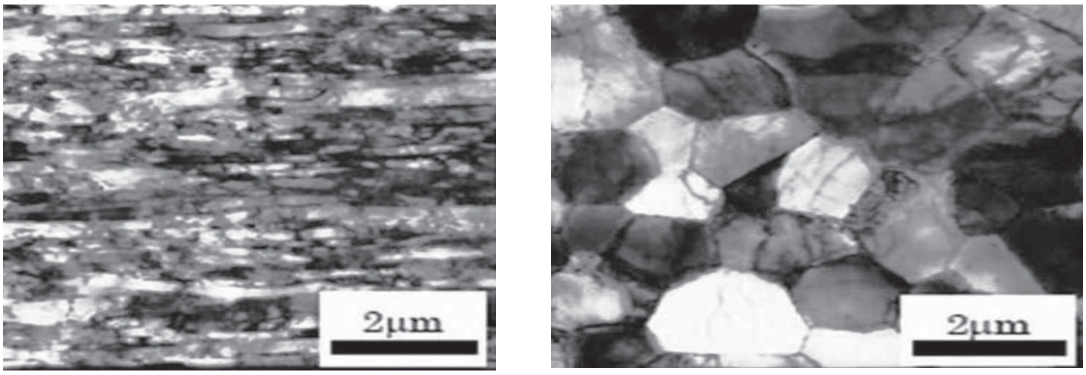
Figure 1 Basic Working Diagram of friction stir welding.

FSW is considered as one of the most significant development in metal joining in the previous years. It is an emerging green technology due to its energy efficiency, sustainable utilization of natural resources, reduced environmental impact and process versatility. These includes low heat input, less

material waste, reduced material lead time, high weld quality, longer life cycle, no shielding gases, fumes and filler material required, adaptable welding orientation, different thickness, microstructures and composition [17-20].

3. MICROSTRUCTURE

The four mutually distinct micro structural regions of friction stir welding are: a) Unaffected zone i.e. base material in which no changes in property occur, b) heat affected zone or HAZ in which microstructure consists of coarse grained structure, c) thermo-mechanical affected zone or TMAZ, the grain size in this zone is finer than HAZ and d) weld nugget which is plasticized and recrystallized due to frictional heat.FSW process involves complex interaction which effect the heating and cooling rate, plastic deformation and flow, dynamic recrystallization phenomena and the mechanical integrity of the joint through simultaneous thermo-mechanical processes [21].In weld nugget zone, intense plastic deformation and frictional heating during FSW results in recrystallization fine grained microstructure. For the ultrafine grain IF steel, grain size of stir zone larger than base material and dislocations in the equiaxis grains is smaller than base materials.



(a) Base metal (b) Stir zone

Figure 2 Image of ultrafine grained IF steel [22].

Fig. 4 shows the microstructure in the stir zone of the friction stir welded joints of the S12C and S35C steels. It has obtained ferrite and pearlite structure with limited amount of pearlite (S12C) are obtained under welding conditions, lower heat input (400 rpm, 400 mm/min).

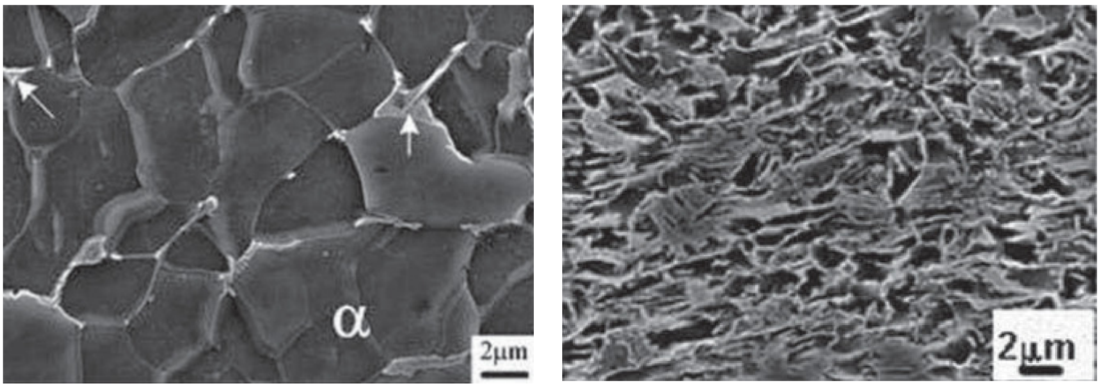


Figure 3 SEM microstructure of the stir zone in S12C and S35C FSW joints [22].

4. FRICTION STIR WELDING PROCESS PARAMETERS

The quality of joint depends on process parameter and tool geometry in FSW process. To improve the quality of weld different parameters such as welding speed, rotational speed, tilt angle and pin geometry lowers the force exerted from thermo-mechanical affected zone to the tool and it also requires less thermal energy for prompting both sheets to reach the plastic state. The various welding process parameters considered in friction stir welding are as follows:

Tool rotation and traverse speeds: The effect of rotation speed and traverse speed (Such as increasing and decreasing respectively) on FSW leads to obtain a quality weld. The material surrounding the tool should be hot enough to enable plastic flow condition and reduce the forces acting on the tool but on the other hand high heat input may harm the final properties of the weld joint [23, 24].

Forces acting on weld: Three forces acting on the tool during welding, such as downward force to maintain the position of the tool, the torque requires to rotate the tool and the traverse force which acts parallel to the tool motion.

Tool tilt and plunge depth: It is defined as depth of the lowest point of the shoulder below the surface of the welding plate. Plunging the tool by increasing the pressure advances adequate forging of the material at the rear of the tool. By tilting the tool (2 to 4 degrees), the rear face of thetool becomes lower than the front face, will assist this forging process and the downward force obtained fully penetrates the weld addressing defects such as pin rubbing on the backing plate surface [24].

Tool Design: Tool design influences material flow and heat generation which in turn leads to quality of weld joints. So the tool material should have the properties such as toughness, wearing resistance along with oxidation resistance and low thermal conductivity.

5. FRICTION STIR WELDING TOOL

A FSW tool consists of different materials and their choice depends upon the type of metal materials to be welded particularly the melting temperature of the material. To induce frictional heat at the work piece interface and cap the plasticized material as it stirred considered being general function of the tool shoulder. Tool is one of the most important factor that influences heat generation, plastic flow, joint efficiency, friction coefficients, microstructure and mechanical properties. The shoulder and pin of the tool influences material flow pattern. To maintain the heat generation and plastic flow a better tool geometry requires which also leads to the uniformity of material along the weld direction. According to TWI, the tapered pin and threaded portion provides more velocities in vertical direction which also favors material flow and uniformity of material along the weld line. Mo and W based tools materials have been used in the joining of AISI 1018 mild steel, 6.3 mm materials [16]. Sato et al. [25] developed Co based alloy tool manufactured at low cost which has yield strength higher than 500 MPa at 1000° C through casting, heat treatment and then machining for joining hard materials. Quayang et al. [26] developed WC-based tool steel functioning material (FGM) to weld high melting material and high abrasive material such as metal matrix composites, steel and titanium alloys. Chung et al. [27] developed a WC based tool materials have been used in the joining of SK5 steel 1.6 mm materials. L. Cui. and H. Fujii. et al. [28, 8] developed a Mo and W based tools to weld Carbon steel 1.6 mm materials. Choi.et al. [29] developed a WC-13% Co; WC-13%Co+6% Ni, 1.5 % Cr_3C_2 tool to weld low carbon steel, 0.6 mm materials.

6. FRICTION STIR WELDING OF STEEL

Nowadays the research is concentrated on FSW of steels because of the major application of steels in the industries. FSW process performed on steels is limited compared to aluminium and its alloys. According to aforesaid studies, increase in welding speed will reduce the crystallized grain size. Also, more heat will be caused by high speed rotating tool due to rubbing the workpiece along tool shoulder.

For high melting material like as stainless steels in FSW, preheating is one of the key factors to make a suitable plastic area [30]. FSW of DH36 steel produces the resultant mechanical properties and micro structural characterization and also expanding on the commonly applied welding speeds. However, fatigue, which is one of important mechanical properties of steel friction stir welds, requires to be investigated in more detail [31]. Fatigue is considered to be the most important failure mechanism for steels particularly, it accounts for almost 90 % of the recorded mechanical service failure [32]. Studies the microstructural evolution and hardness distribution in the welds of 2 mm and 6 mm thick 304 austenitic stainless steel plates [33]. The microstructural features of 304 stainless steel welded plates. Welded was performed on 11 KW vertical milling machine on 2.5mm plate. The tool used was tungsten based alloy they found out that tungsten carbide tool yielded good results [34]. When compared to IF steel, S12C and S35C are affected by welding conditions. It is evident that in ferrite austenite two phase regions the microstructure is distinguished. The strength of S12C and S35C steel joints increased by increasing the welding speed [8]. Grain refinement in the SZ of 304L stainless steel during FSW showed overmatched tensile properties and higher hardness of the welds [35, 36]. Stated that the SZ of 304L stainless steel initially undergoes dynamic recrystallization [37]. FSW produces disparate distribution of dislocation densities within the resultant microstructure due to the non-uniform deformation in the process. Based on the subsequent heating of the tool shoulder, those regions of high dislocation density undergo static recrystallization. For S70C (0.70 % C) high carbon steel. This is an almost completely eutectic high carbon steel since, when this kind of metal is subjected to conventional fusion welding, there is an almost complete production of marten site and the joint becomes very brittle, resulting in welding becoming very difficult [9]. When 1.5 mm thick 304 stainless steel sheets are welded at 1 m/mm, 100% joint efficiency is obtained [38, 39]. Butt welded 1.6 mm thick 780-1180 N/mm^2 high tensile steel sheets and used the results to evaluate the range of approximate conditions. Using a tool of ultra-hard alloy (WC) at a rotation speed of 200 rpm to reduce the heat input, they were able to obtain a joint with no defects and only slight HAZ softening [40,41]. Hard metal carbide tools (K10, 94 % WC- 6 % Co) with triangular pin geometry are suitable for FSW process of AISI 304 austenitic stainless steels [42].

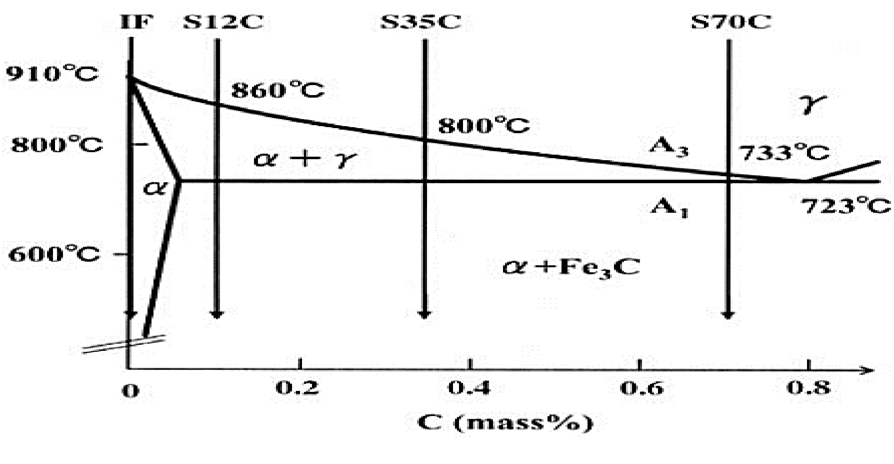


Figure 4 Fe–Fe_3C phase diagram [8].

7. MECHANICAL PROPERTIES OF STEEL

Many studies have been carried out about the FSW of carbon steels till now. In the HAZ, the hardness of the base metal increased from 200 HV to a range of 750-850 HV in the weld center and the external heat on the hardness profile was negligible. In case of interstitial free (IF) steel, the welding speed does not affect the hardness profiles of the joints, while for the S12C steel, the hardness increases as the welding speed (the smaller heat input) increases. As the welding speed exceeds more than 200

mm/min, the tensile strength of IF steels joints decreases, S12C and S35C steel joints got increased. Mechanical properties of steel weld produced by FSW have improved mechanical properties compared to the base material. The weld regions generally possess higher hardness although the hardness profile depends on the steel type and the welding conditions [8]. The mechanical properties of a tensile strength of 1432 MPa and an elongation of 11 % are obtained at 400 rpm and 25 mm/min, if the rotation speed is reduced to 200 rpm, it is possible to reduce the cooling rate further and to obtain a microstructure that is completely pearlite. In such cases, the elongation is greatly improved [9]. The friction stir welding of 2mm thick high nitrogen-containing stainless steel at a welding speed of 100 mm/min, which had the best mechanical properties to relatively higher Vickers hardness [11]. The feasibility of FSW in welding of mild steel (AISI 1018) by Lienert.et.al demonstrated the significant effect of peak temperature on the microstructures and mechanical properties of the different carbon steels (IF steel, S12C, S35C) without loss of tensile properties [16]. This is mainly due to the formation and uneven distribution of martensite in the weld region. The main factor in heat generation and heat input issues are rotational and travelling speeds. Generally, Lower heat input in friction stir welding cause improves mechanical properties as well as low distortion and decrease in residual stress. The strain rate that can help to understand the FSW, which has a special role in determining the speed of welding. Strain rate is essential to understand the material flow in stir zone. Thus, scholars have tried to find strain rate during FSW in their studies [30]. Steel friction stir welds have exhibited exceptional fatigue lives, well above 10^5cycles to fracture, even at a stress range of 90 % of yield strength of the base material and away from the weld prove that except for the yield strength, static loading does not carry important information on the steels performance in real environments, where cyclic loading is the dominant stress mechanism [31].

The hardness of SZ found to be more than that of base material and the location of maximum hardness found in TMAZ due to high density of dislocations and sub-grains [33]. For butt welded 1.6 mm thick high tensile steel sheets, it is possible to weld 980 N/mm^2 steel with a joining efficiency of at least 95 %. The joining efficiency was also 84 % with 1180 N/mm^2 steel [40, 41].In FSW, the maximum tensile strength of AISI 304 material formed with 950 rpm rotational speeds and 60 mm/min traverse speed, 9 kN compressive tool force, and 1.5° tool tilt angle the weld zone was determined to be as 430 MPa while the tensile strength of the parent material is 505 MPa [42]. Compared with GTAW (gas tungsten arc welding) joint, the tensile and elongation properties of FSW joints of interstitial free (IF) steels provides better weld [43]. In comparison to FSW of low carbon alloy and mild steels, FSW on hyper-eutectoid steel (AISI 1080) has been performed with better toughness and ductility due to absence of martensite [44]. The reported less martensite formation using a gas torch in FSW of SK5 (0.84wt % C) steel. They demonstrated the reliability of the FSW that the tensile strength of different cases was the same as that of the base metal [45].

In SK5 steel, the base metal possesses an ultimate tensile strength of 610 MPa. Tensile specimens were fractured at the base metal [46]. Fine grained ferrite with pearlite structure is observed in the weld regions making the tensile strength more, because of the elevated temperature in the region of ferrite-austenite two phase region [8, 47]. When shoulder diameter 20 mm is used for welding AISI409M ferritic stainless steel of 4 mm thick, highest tensile strength is achieved but increase in shoulder diameter leads to decreases impact toughness [48].In hydrogen embrittlement of FSW on high carbon steel. However, the ultimate strength and elongation reduction can be decreased [49]. The grains transformed to fine ferrite and pearlite by cooling the material after FSW with fine grains increased the hardness and strength in the stir zone [50].

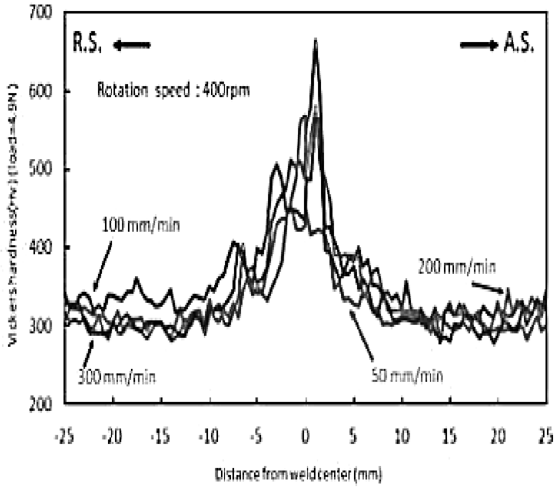


Figure 5 Vickers hardness of nitrogen containing austenitic stainless steel at various welding speed and a constant rotating speed at 400 rpm [11].

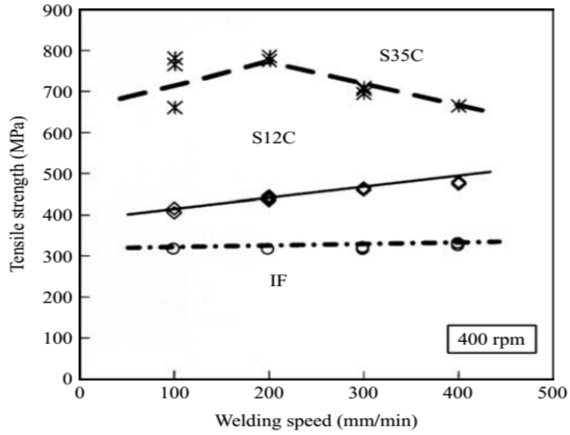


Figure 6 The relationship between welding speed and Tensile strength in IF, S12C and S35 [8].

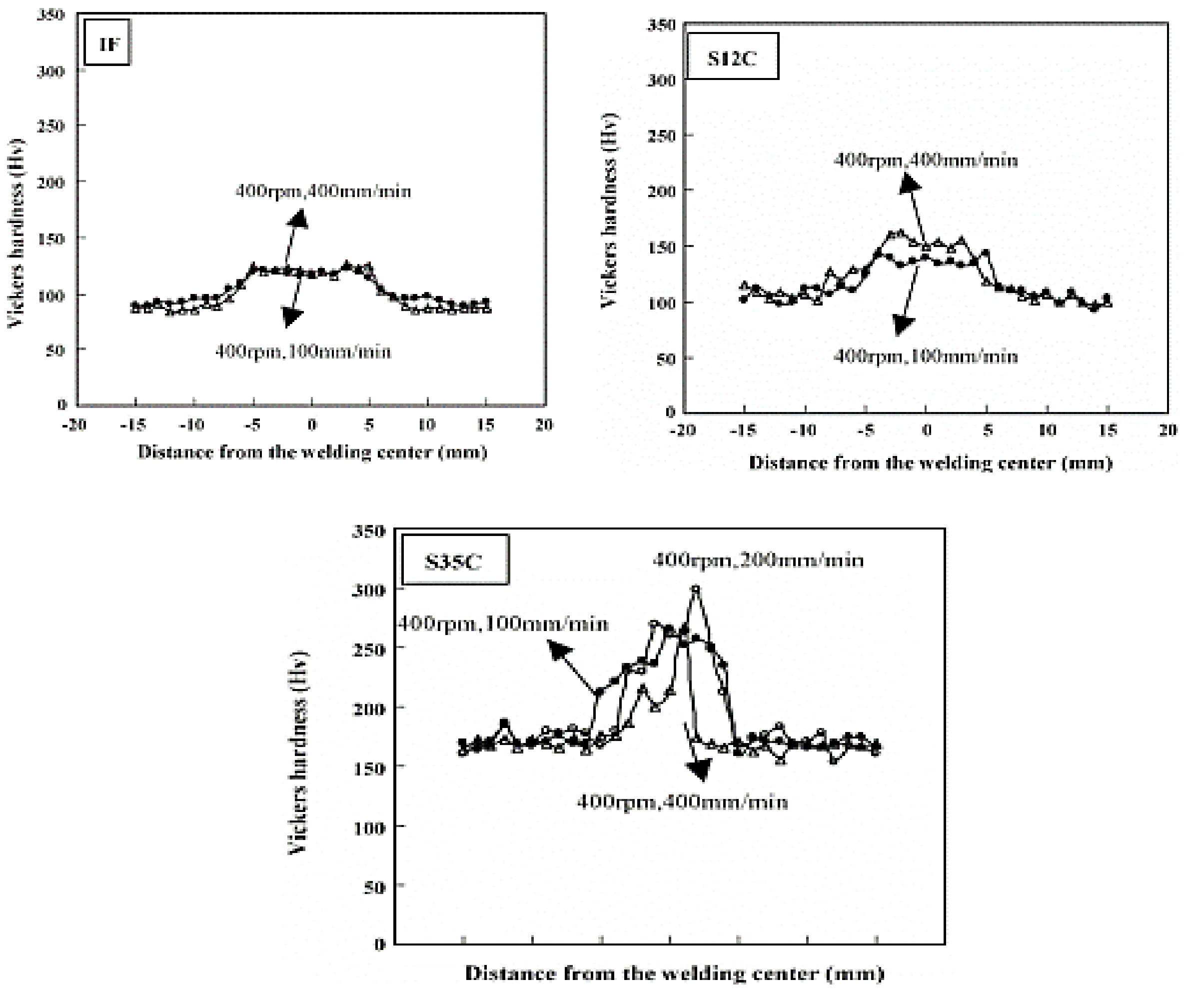


Figure 7 Hardness of IF steel, S12C and S35C [8].

8. ADVANTAGES AND LIMITATIONS OF FRICTION STIR WELDING PROCESS

8.1. Advantages

In general, FSW and its related processes are characterized by being solid phase joining techniques, thermo- mechanically energy efficient. In this process is no exception and in addition the welding operation is easy and handling friendly. Recent advantages of the process are:

- The process is machine tool based, which can be semi-automatic or fully automated or essentially an autogenous, non-consumable keyhole technique, eliminating problems associated with selection and storage of consumables and also can be carried out in all position e.g. vertical and overhead.
- The process is relatively quiet easy to automate and user friendly and solid phase and it does not normally require a shielding gas for most of the materials.
- High integrity welds are produced and weldments have comparatively low distortion level which can carried out without the spatter, ozone formations or visual radiation associated with fusion welding technique.
- Surface appears to be rough which in most cases reduces production cost in further processing and finishing.
- Square edged abutting plates are needed for a butt joint which saves consumable material, time and money.
- Plain low carbon steel and chromium alloy steel can be welded with thicknesses of 3-12 mm and also up to 25mm. It can be welded from sides as in case of arc welding.
- Once established whole line of point, Optimized process conditions can be preset and subsequent in process monitoring can be used as a first line check that weld quality is being maintained.
- Overall setup is simple with relatively low running costs.
- FSW is also environmental friendly and can be carried out under water.

8.2. Limitations

- To prevent the abutting plates moving apart, it is necessary to clamp the work piece materials firmly and suitable jigging and backing bars are also needed.
- An end of run hole is left as the probe is withdrawn, this problem can be overcome by using a hole filling technique such as taper plug or friction hydropillar welding.
- For plain low carbon steel and to a lesser extent 12% chromium steels possess tool wear limiting feature and the welding traverse speed is typically 1.7-4 mm/s and, which could be considered comparatively slow for relatively thin plate material.

9. CONCLUSION

In conclusion, Friction Stir Welding is one of the cost effective and long life tools which is available for the steels and other high melting alloys. Since its inception, FSW technology has been a major boon to advanced industries. Within less span of time it has found widespread applications in diverse industries. On the basis of efficiency required high melting alloys such as steel and other structural alloys can now be welded using this process. Compared to the BM, mechanical properties are also improved. Tool geometry, welding parameter, traverse speed, plunge depth, spindle angle, material types, work-piece temperature are the factors that can influence the material flow during FSW. Most of the welds is done with cylindrical pin profile, but there are some applications in truncated pin profile. Tapered pin tool give us better mechanical properties throughout the length of the plate as describe in tool geometry. Past two decade maximum work have been done low melting material, less

tied to weld hard materials due to the lack of tool material and tool design. Further developments in FSW tools for hard materials to address the problem of high tool cost with low tool life during welding.

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